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Heat Activated Prestressing of $Ni_{48.46}Ti_{36.03}Nb_{15.42}$ Shape Memory Alloy for Active Confinement of Concrete Sections

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ABSTRACT: This paper presents the results from the experimental investigation on *heat activated prestressing* of Shape Memory Alloy (SMA) wires for active confinement of concrete sections. Active confinement of concrete is found to be much more effective than passive confinement. Active confinement achieved using conventional prestressing techniques faces many obstacles due to practical limitations. A class of smart materials that has recently drawn attention in civil engineering is the shape memory alloy which has the ability to undergo reversible hysteretic shape change known as shape memory effect. The shape memory effect of SMAs can be utilized to develop a convenient prestressing technique for active confinement of concrete sections. In this study a series of experimental tests are conducted to study thermo-mechanical behaviour of $Ni_{48.46}Ti_{36.03}Nb_{15.42}$ (wt. %) SMA wires. Although, numerous studies on active confinement of concrete using NiTiNb SMA have been carried out in the past, no particular study on $Ni_{48.46}Ti_{36.03}Nb_{15.42}$ exists in the literature. A series of tests were conducted in this study to characterize the material properties of $Ni_{48.46}Ti_{36.03}Nb_{15.42}$ for active confinement of concrete sections. Parameters such as *heat activated prestress* (HAP), residual strain and the range of strain that can be used for effective active confinement after HAP were investigated in detail. The influence of pre-strain and temperature on HAP was also investigated. It was found that a significant amount of HAP can be developed in pre-strained $Ni_{48.46}Ti_{36.03}Nb_{15.42}$ upon heating, most of which is retained at room temperature. A substantial amount of strain recovery upon unloading and after heating was recorded in all tests. The range of strain available for effective active confinement was also found to be significant. The results from this study demonstrate that the chemical composition of NiTiNb along with level of pre-strain and the corresponding transformation temperature range significantly affects the HAP, which in turn can affect the efficacy of the retrofitting strategy in which NiTiNb is used as a means to apply active confinement.

KEY WORDS: Shape memory alloys, Heat activated prestressing, Active confinement of Concrete.

1 INTRODUCTION

Reinforced concrete (RC) buildings are probably the most popular choice of construction around the world for ease of construction and economic reasons. However, many RC buildings have exhibited poor performance during past earthquakes such as 1999 Kocaeli (Turkey) earthquake [1] and 2008 Wenchuan (China) earthquake [2]. One of the main reasons being most earthquake resistant design codes were only developed and implemented after the 1970's. Reinforced concrete buildings built prior to 1970's were designed to carry only gravity loads. These 'gravity load only' designed buildings possess many inherent deficiencies to withstand strong ground motions for example, inadequate shear strength and ductility of columns, inadequate shear strength of beam-column joint core, insufficient lap-splice length of rebars in plastic hinge zone and insufficient anchorage of beam rebars framing into the joint core. Without retrofitting, these deficiencies pose a significant fatality hazard and may lead to partial or complete collapse of buildings during strong earthquakes.

Over the past few decades, the importance of retrofitting these buildings has increased many folds. Many retrofitting strategies have been developed during the past few decades. Most of them oriented to increase ductility of these buildings. The majority of these retrofitting strategies fundamentally involve confining structural elements. Traditionally, concrete or steel jacketing has been employed to confine concrete section at key locations. As an alternative to concrete and steel jacketing, fibre reinforced polymer (FRP) composite materials introduced in late 1980's also provide an easy to apply and light weight means to confine and reinforce RC sections. However, either of these techniques provide only passive confinement i.e., the confining pressure is developed only when the concrete starts to dilate upon loading. Conversely, if the confining pressure is applied before the application of the load, known as active confinement, the strength and ductility of the member can be further enhanced.

The concept of active confinement has been studied in the past by many researchers. Yamakawa et al. [3] investigated active confinement of concrete using prestressed aramid fiber belts and reported that active confinement of concrete contributes significantly to increasing the shear strength, axial load carrying capacity and restraint to circumferential strain of concrete. Moghaddam et al. [4] used prestressed metal strips to actively confine concrete prismatic and cylindrical specimens. Their experimental work demonstrated a significant increase in strength and ductility of actively confined concrete sections. However, in spite of encouraging results from these works, applying these active confinement retrofitting techniques to the real structures using conventional mechanical pre-stressing methods faces many obstacles due to a number of practical limitations.

A class of smart materials that has recently drawn attention in active confinement strategies are the Shape Memory Alloys (SMAs). SMAs belong to a group of smart materials which have the ability to undergo large deformations with minimum residual strain, a behaviour known as *pseudoelasticity* or *superplasticity* (SE). SMAs also have the ability to undergo reversible hysteretic shape change known as *shape memory effect* (SME).

SMAs in general offer a wide range of possible application in civil engineering. This study focuses only on application of SMAs in active confinement of concrete sections. Several researchers [5-8] have studied active confinement of concrete using SMAs and reported a significant enhancement in the strength and ductility of retrofitted sections. A brief overview of the thermo-mechanical properties of SMAs is given in the next section.

2 THERMO-MECHANICAL FEATURES OF SMAs

SMAs have two distinct phases, each with different crystalline structure. The phases stable at low temperatures and high stresses is called *martensite* phase (M-phase) and the phase stable at high temperature and low stresses is called *austenite* phase (A-phase). The associated transformation from one phase to another results from reversible shear lattice distortion [9] and forms the basis of the unique behaviour of SMAs. A schematic explanation of phase transformation is given in the Figure 1.

The mechanical properties of SMAs are highly dependent on the temperature and the phase in which it is used. There are four characteristic temperatures associated with the phase transformation. SMAs in M-phase begin to transform into A-phase when the temperature is increased beyond *austenite start temperature* (A_s); complete transformation from M-phase to A-phase takes place only when temperature is increased beyond *austenite finish temperature* (A_f). Once in A-phase SMAs behaves as *pseudoelastic* material and recovers most of the deformation upon unloading, see Figure 1(c).

Similarly, if the temperature of A-phase SMAs is reduced below *martensite start temperature* (M_s), phase transformation from A-phase to M-phase starts to take place. A complete transformation from A-phase to M-phase takes place only when temperature is reduced below *martensite finish temperature* (M_f). In this phase, SMAs retain majority of the deformation upon unloading (See Figure 1(b)). A more elaborated explanation on this behaviour can be found elsewhere [9, 10].

If a sufficient mechanical load is applied to SMAs in the M-phase or the intermediate phase between M-phase and A-phase, a considerable amount of strain is retained upon unloading. A subsequent heating of the SMA results in a significant amount of strain recovery; leaving behind only a minimal residual strain. However, if the strain recovery is restrained by anchoring the ends of SMAs a considerable amount of prestress can be generated in SMAs. This phenomenon can be conveniently utilised for actively confining concrete sections.

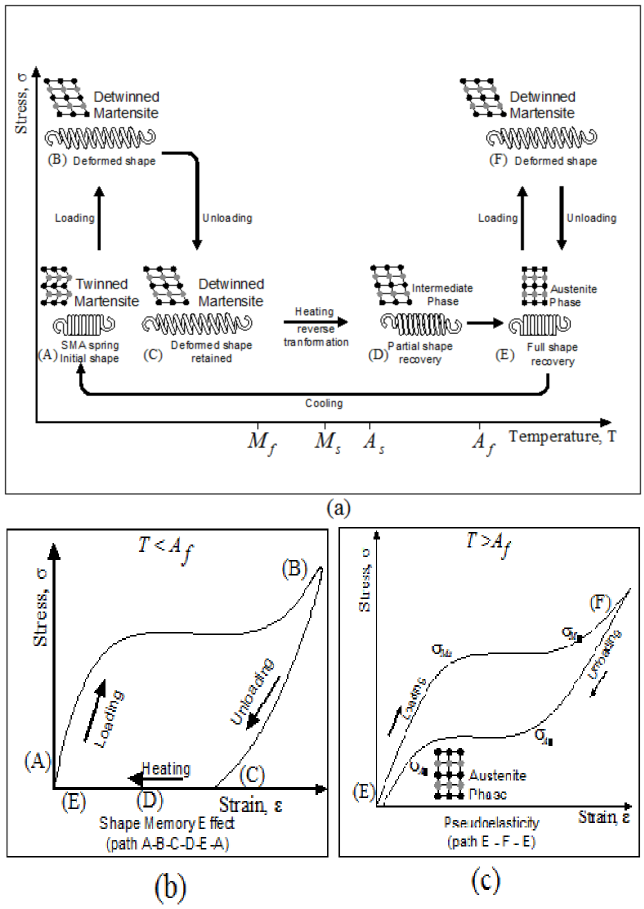


Figure 1. (a) Schematic of the one way shape memory effect (path A-B-C-D-E-A) and pseudoelasticity (path E-F-E) of an SMA spring; (b) stress-strain curve of SMA in M-phase; and (c) stress-strain curve of SMA in A-phase. Excerpts from [11].

3 EXPERIMENTAL PROGRAM

The behaviour of SMAs is complex and depends on a number of parameters. Depending upon the alloying elements, SMAs exhibit different behaviour in different conditions and are highly sensitive to variation in temperature, phase in which it is used, loading pattern and pre-strain conditions. Existing studies on active confinement of concrete sections using SMAs have shown that not all SMAs are suitable for this application. For active confinement, the phase transformation temperatures of SMAs needs to be such that the pre-strain required to cause reverse transformation is retained at room temperature. The transformation temperatures of SMAs depend not only on the alloying elements but also on the proportions in which they are combined. Among the existing group of SMAs, NiTiNb has been found to be the most suitable SMA for active confinement. Further, many different compositions of NiTiNb has been studied in the past. It has been found that different compositions of NiTiNb can have significantly different behaviour. In this project $Ni_{48.46}Ti_{36.03}Nb_{15.42}$ wires are used as a material for active confinement of non-seismically designed reinforced concrete sub-assemblies. No detailed study on $Ni_{48.46}Ti_{36.03}Nb_{15.42}$ could be found in the literature. Therefore, a detailed thermo-mechanical characterization of NiTiNb was required before using it for the actual retrofitting.

This paper presents some results obtained from heat activated pre-stress tests conducted on $Ni_{48.46}Ti_{36.03}Nb_{15.42}$ wire specimen specimens.

4 HEAT ACTIVATED PRE-STRESS TESTS

4.1 Material Specifications

The chemical composition of NiTiNb used in this study was provided by the supplier and is given in Table 1.

Table 1. Chemical composition of SMAs used in this study (values given in % of weight)

Ti	Ni	Nb	C	N	H	O
36.03	48.46	15.42	0.039	0.004	0.001	0.042

The initial transformation temperatures of undeformed NiTiNb wire obtained from differential scanning calorimetry (DSC) tests were also provided by the supplier and are given in Table 2.

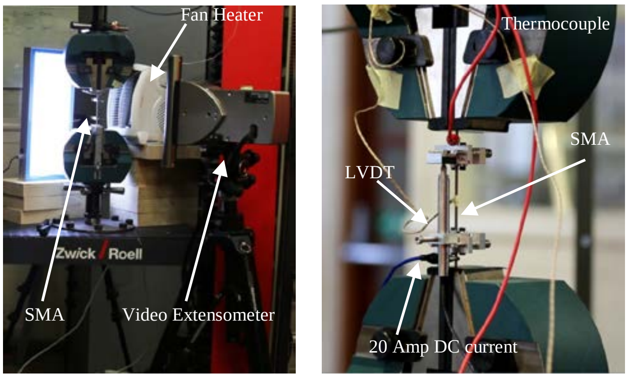
Table 2. Transformation temperature of $Ni_{48.46}Ti_{36.03}Nb_{15.42}$ used in this study (°C)

M_f	M_s	A_s	A_f
-100	-78.79	-22.0	3.5

4.2 Test Setup

All $Ni_{48.46}Ti_{36.03}Nb_{15.42}$ (hereafter referred to as NiTiNb only unless the exact composition is necessary to mention) wire specimens used in this study were tested on a Zwick Roell universal testing machine. The machine was installed with a 100kN load cell having an accuracy of ±0.02% of the applied load between the range of 0-5kN. Several types of grips were tried to anchor the NiTiNb wires. Although direct slippage was prevented using wedge type grips, it was impossible to prevent minor slippage due to the embedment of the grip teeth in the wire specimen. Therefore, average strain measurement using crosshead travel data was discarded. Instead, strain was measured using noncontact single camera video extensometer or, in some cases, single Linear Variable Differential Transformer (LVDT) attached to the specimen. The details of the test setup are shown in Figure 2.

Two different techniques were used for heating the NiTiNb wire specimens. In the first instance, a 20 Amp DC current was passed through the wire specimen. However, due to heat loss through end grips and LVDT clamps attached to the wire, using this technique the temperature was raised only up to 100-120°C. Further increase in current to 40 Amp would have raised health and safety issue and therefore, this method was discarded. In the second approach the specimens were heated using fan heaters supplemented with a heat gun. This method was preferable as the heating process in the final application is also planned to be carried out using heat gun. The temperature of the wire specimens was recorded using Type-T thermocouple attached directly to the surface of the specimens as shown in Figure 2.



(a) (b)

Figure 2. Test setup for thermo-mechanical tests of $Ni_{48.46}Ti_{36.03}Nb_{15.42}$ wire specimens. (a) Video extensometer used for measuring strain; heating carried out using fan heater and heat gun. (b) LVDT used for measuring strain; heating carried out using 20Amp DC current.

4.3 Test Plan

Results from three different types of tests viz. Test -1, Test-2 and Test -3 are presented in this paper. The tests were carried out to study parameters such as *heat activated prestress* (HAP), residual strain and the range of strain that can be used for effective active confinement after HAP. The influence of pre-strain and temperature on HAP was also investigated. $Ni_{48.46}Ti_{36.03}Nb_{15.42}$ wire of 2 mm diameter was used for all the tests. In the first test (Test-1), the wire specimen was pre-strained, heated above the austenite finish temperature and immediately unloaded after heating. In the second and the third tests (Test-2 and Test-3), specimens were loaded cyclically after heating. The cyclic loading of wire specimens after heating was carried out to determine the range of strain that could be used for active confinement.

NiTiNb specimens in Test-1 and Test-3 were pre-strained by 6% while in the Test-2 the specimen was pre-strained by 2.25%. NiTiNb wire used in the Test-2 was reused in Test-3 to investigate the behaviour of reused NiTiNb specimen.

4.4 Test Results

Test -1

In Test-1, the NiTiNb wire specimen was loaded to 6% strain (path A-B-C in Figure-3) and then unloaded to zero stress level (path C-D). Both loading and unloading were carried out in strain controlled manner at a strain rate of 0.003/sec. A gauge length of 50 mm was adopted in all the tests.

A yield stress equal to 638 MPa and a maximum stress of 733 MPa (Point C in Figure 3) were recorded before unloading. Once the specimen was unloaded to zero stress state (Point D in the Figure 3), heating was carried out in two stages keeping both ends of the specimen anchored throughout the heating process.

In the first stage of heating, the specimen was heated using two 2000 Watt fan heaters (up to point M in Figure 4) up to 125ºC. Since an increasing trend in HAP was observed, it was decided to keep increasing the temperature. A supplementary heating was provided using a 2000 watt heat gun. The wire heating was stopped at 230ºC (Point E in Figure 4) after a plateau in the stress vs temperature plot (Figure 4) was observed. The wire was then allowed to cool down naturally to the room temperature.

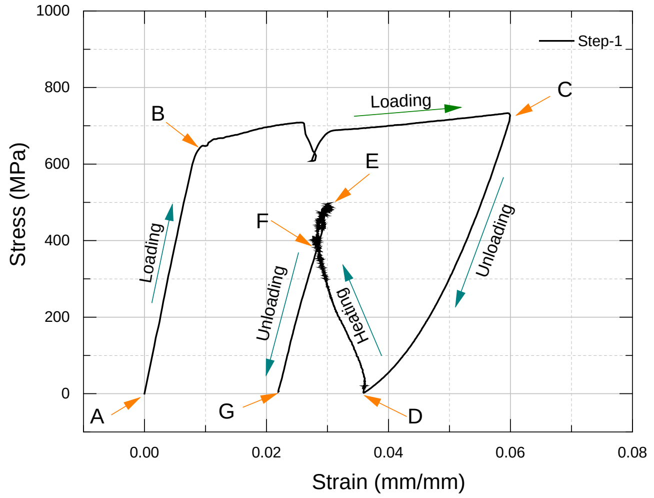


Figure 3. Stress vs strain obtained from Test-1

The max HAP achieved during the heating process was 498 MPa. On cooling to room temperature, a slight reduction in HAP was observed. HAP retained at room temperature was 438 MPa.

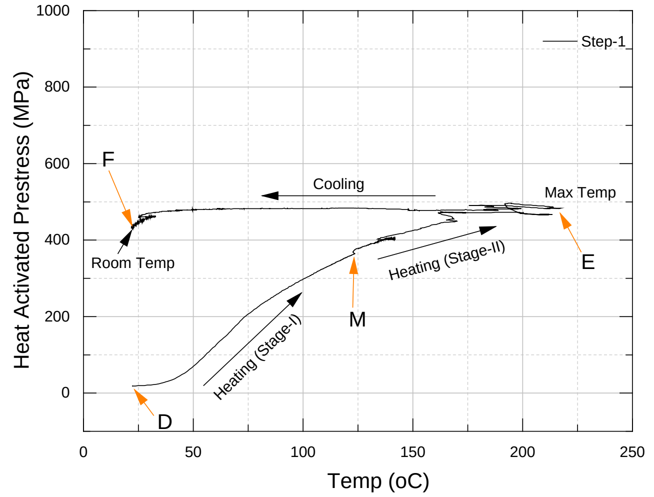


Figure 4. HAP vs temperature obtained from Test-1

Once the material cooled down to the room temperature (Point F in Figure 3 and Figure 4), the specimen was held in place for 1 hour to observe any HAP loss at room temperature. An insignificant HAP loss was observed during this time indicating HAP is only temperature dependent and no short term creep effect was observed. However, long term creep effect should be investigated separately. The specimen was then unloaded and a residual strain of 2.1% was recorded (Point G in the Figure 3). HAP recorded in the wire specimen during the heating and cooling process is plotted in Figure 3 (path D-E-F) and Figure 4 (path D-E-F).

Test-2

In Test-2 the SMA wire was pre-strained by 2.25% and then unloaded as shown in Figure 5 (path A-B-C-D). A yield stress equal to 608 MPa was measured and the specimen was unloaded at a stress of 638 MPa (point C in Figure 5).

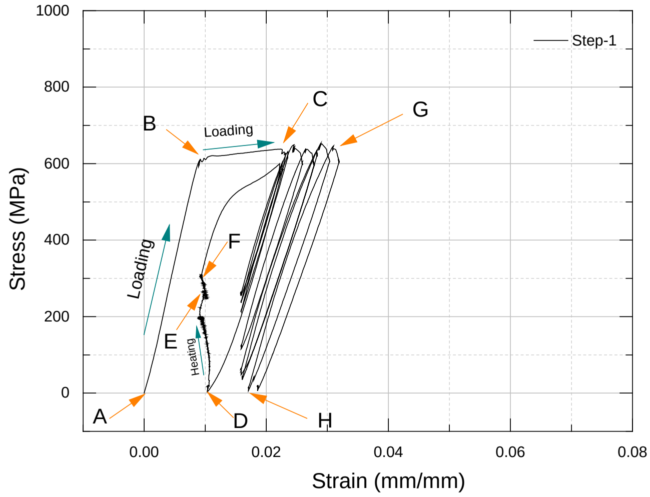


Figure 5. Stress vs strain obtained from Test-2

Once unloaded, the wire was heated in the same way as in Test-1. Upon heating, the HAP produced in the wire kept increasing until a temperature of 153ºC was reached, it then decreased linearly until heating was stopped at 215ºC as shown in Figure 6.

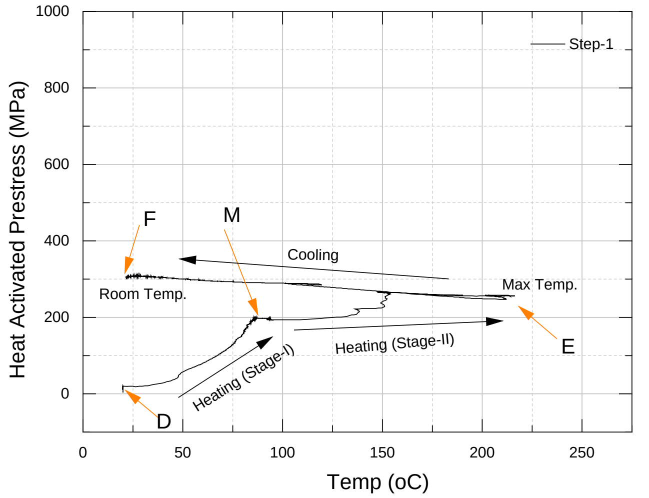


Figure 6. HAP vs temperature obtained from Test-2

The behaviour of NiTiNb wire shown in Figure 6 was found different from Test-1, in which the HAP gradually increased until a max value was achieved. Unlike in Test-1, on cooling, the wire specimen in Test-2 showed a gradual increase in HAP from 253 MPa at max temperature to 306 MPa at 25ºC. After cooling, the wire was left undisturbed at room temperature for about 1 hour, no major change in HAP was observed during that time. The wire specimen was then cyclically loaded to study the response of prestressed NiTiNb wire under cyclic loading. The cyclic loading was carried out in such a way that unloading was always restricted to strain of 1.5% as shown in Figure 5. This was done to simulate a hypothetical situation in which

NiTiNb wire confining a concrete section would be restricted to contract beyond the actual cross-section of the concrete. The cyclic loading was ended when the stress level at unloading reached zero (corresponding to a strain value of about 1.66%), see point H in Figure 5. The difference in the strain between Point D and Point H in Figure 5 provides the range of strain for which HAP can be effectively used for active confinement. This range in Test-2 was 0.66%.

Test-3

Wire specimen used in Test-2 was reused in Test-3. The specimen was pre-strained by 6% (path A-B-C in Figure 7) and then unloaded to zero stress level (path C-D) in Figure 7.

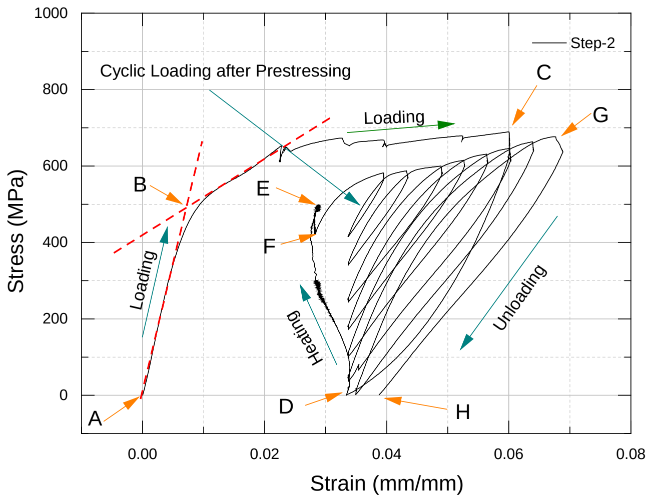


Figure 7. Stress vs strain obtained from Test-3

The yield stress of the specimen used for Test-3 was 491 MPa, see Figure 7. This reduction of yield stress was consistent with other tests performed afterwards. The yield stress was determined as shown in Figure 7 as the stress value of point B. It is worth noting that the stress vs strain plot shown in Figure 7 corresponds to loading in Test-3 only and does not include the residual strain equal to 1.82% measured at the end of Test-2.

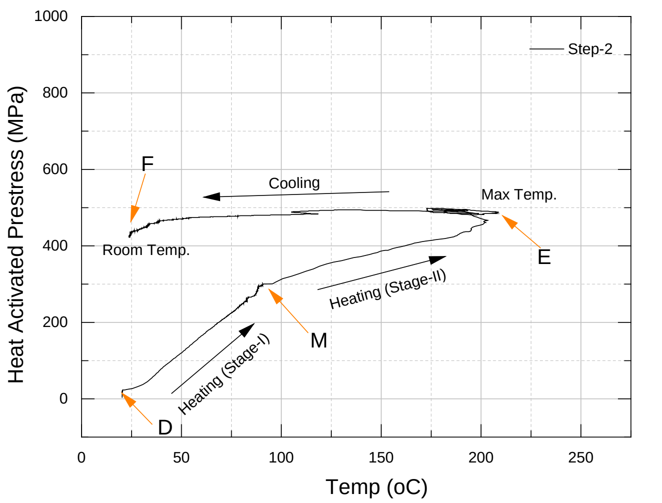


Figure 8. HAP vs temperature obtained from Test-3

Once the specimen was unloaded to zero stress state (Point D in the Figure 7), the specimen was heated in two stages in the same way as in Test-1 and Test-2. Heating was stopped at about 215ºC. The max HAP achieved during heating process was recorded equal to 495 MPa at 200ºC. On cooling the wire to room temperature, a slight reduction in HAP was observed. The HAP retained at room temperature was 427 MPa. HAP recorded in the wire specimen during heating and cooling process is plotted in Figure 7 (path D-E-F) and Figure 8 (path D-E-F).

After the heating and cooling process, the wire specimen was cyclically loaded as shown in Figure 7. Unloading in each cycle was restricted to strain value corresponding to Point D in Figure 7. The amplitude of each loading cycle was increased incrementally until HAP reduced to zero upon unloading. The range of strain between Point G and Point D in Figure 7 was recorded equal to 3%. This strain range can be effectively used to confine concrete actively. Beyond this strain range, the confinement will act as passive confinement.

5 DISCUSSION

With an austenite finish temperature (A_f) of 3.5ºC, the $Ni_{48.46}Ti_{36.03}Nb_{15.42}$ wire specimens were expected to behave *pseudoelastically* at room temperature which ranged between 17ºC and 25ºC. However, a significant amount of residual strain was retained after unloading the specimens from point C in all the tests; indicating the shift in the phase transformation temperatures. A similar behaviour in $Ni_{47.45}Ti_{37.86}Nb_{14.69}$ was found by Choi et. al [7]. During the tests non-uniform reduction in cross-sectional area was observed in all the specimens' up to the strain of 6%, implying that *detwining* in $Ni_{48.46}Ti_{36.03}Nb_{15.42}$ takes place in the bands of small lengths distributed non-uniformly along the length. When heated, these bands transform back to austenite phase and lead to strain recovery.

The maximum HAP recorded in Test-1 and Test-3 specimens, both pre-strained by 6%, was 498 MPa and 495 MPa respectively, while as HAP measured in Test-2 in which specimen was pre-strained by 2.25% was recorded only 308 MPa. HAP appears thus to be directly influenced by the amount of pre-strain. HAP measured in $Ni_{48.46}Ti_{36.03}Nb_{15}$ in this study was found to be substantially greater than HAP measured in $Ni_{47.45}Ti_{37.86}Nb_{14}$ [7].

The loss in the HAP on cooling was equal to 60 MPa (12%) in Test-1 and 68 MPa (13.7%) in Test-3. On the contrary, in the Test-2 the HAP increased by 53 MPa (20.9%) on cooling. Since the room temperature varied between tests, the HAP retained at 25ºC in Test-1 and Test-3 both being pre-strained by same amount were compared to eliminate the influence of temperature. In Test-1 HAP at 25ºC was 452 MPa while as in the Test-3 HAP of 436 MPa was recorded at 25ºC. A difference of 16 MPa at 25ºC can be found between the two tests.

In Test-1 the elastic strain recovered upon unloading was equal to 2.4% and the residual strain retained before the heating and cooling process was 3.6% (strain between Point A and D). In Test-3, the elastic strain recovered upon unloading was 2.67% and the residual strain retained was 3.33%. The slight increase in elastic strain recovery and a slight decrease in residual strain recovery of the Test-3 specimen may be attributed to the influence of the loading history during Test-2. Loading history appears to affect not only the HAP but also the yield stress. A reduction of 119 MPa in the yield stress was observed when the NiTiNb was reused in Test-3.

A residual strain of 2.1% after HAP was recorded in Test-1. This strain may be regarded as permanent unrecoverable plastic strain in the specimen. During the heating process, some amount of strain was recovered (path D-E in Figure 3) within the gauge length. Similar trend was observed in Test-2 and Test 3 (path D-E in Figure 5 and 7). This strain recovery may be due to rearrangement at microscopic level. Since the grip to grip distance was kept fixed while heating, the strain recovery within the gauge length indicates non-uniform contraction and extension of individual hypothetical bands along the length of the specimens as discussed above.

The ability to develop HAP in NiTiNb can be conveniently used to actively confine concrete sections. As discussed above a significant portion of HAP produced in NiTiNb is retained at room temperature. In the practical applications, if the pre-strained NiTiNb wires are wrapped and anchored around the concrete section; with a simple heating procedure a significant amount of active confining pressure can be applied quite easily. In this study a 6% pre-strain is found to produce a significant amount of prestressing force however, depending upon the nature of applications different pre-strain levels can be tried. A detailed discussion on the influence of HAP and pre-strain level will be presented separately.

It is important to note that once a section that is actively confined with NiTiNb is cyclically loaded, depending on the level of strain imparted in the loading cycle, HAP is reduced upon unloading. Implying that HAP in NiTiNb for next loading cycle will be less than that in the previous cycle. The reduction in HAP with the increase in strain level in the loading cycle continues until it is completely lost. Beyond this point NiTiNb confinement will acts as mere passive confinement. In order to determine the range of strain within which NiTiNb confinement will effectively apply active confining pressure, NiTiNb specimens in Test-2 and Test-3 were cyclically loaded and unloaded until the HAP became zero. The range of strain for which the HAP was found effective was about 3% in Test-3 corresponding to pre-strain value of 6%. A range of 3% can significantly contribute in enhancing ductility and strength of concrete sections.

6 CONCLUSIONS

Three different types of tests have been conducted on $Ni_{48.46}Ti_{36.03}Nb_{15}$ wire specimens to assess its suitability for active confinement of concrete members in engineering structures. The results presented in this paper show that:

- The chemical composition of SMA is an important aspect to consider while choosing the type of SMA for active confinement.
- Pre-strain can significantly influence the level of HAP achieved in SMAs.
- $Ni_{48.46}Ti_{36.03}Nb_{15}$ can be used in wide variety of applications in civil engineering. It offers a convenient option for applications involving pre-stressing. It can be easily employed for effective active confinement of concrete members in engineering structures.
- HAP of about 500 MPa can be achieved in $Ni_{48.46}Ti_{36.03}Nb_{15}$ SMA when pre-strained by 6%. About 450 MPa of which is retained at 25ºC. With this range of HAP, $Ni_{48.46}Ti_{36.03}Nb_{15}$ can be used to significantly increase the ductile and the strength of a poorly detail reinforced concrete member.
- A substantial amount of strain recovery is observed in $Ni_{48.46}Ti_{36.03}Nb_{15}$ wires. About 2.5% elastic strain recovery upon unloading from 6% strain level is observed. In the specimen pre-strained by 6%, a total of 4% strain is recovered when unloaded after heating.
- A 6% pre-strain in $Ni_{48.46}Ti_{36.03}Nb_{15}$ can avail a strain range of 3% for effective confinement after HAP. This range of strain can significantly enhance the ductility and strength

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